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Published in:
Physics Letters B

DOI:
10.1016/0370-2693(87)90337-6

Publication date:
1987

NEUTRON DECAY OF THE GIANT MONOPOLE RESONANCE IN ^{124}Sn

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Received 2 June 1987

The neutron decay of the isoscalar giant monopole resonance (GMR) and of the underlying continuum in ^{124}Sn was studied. The GMR decay mechanism is shown to be a function of the excitation energy. The non-statistical decay component decreases with excitation from (20 ± 5)% in the lower part to (10 ± 5)% in the higher part. For the lower part there is evidence for pre-equilibrium decay. The decay of the continuum also shows a non-statistical decay component.

Several mechanisms play a role in the decay of giant resonances. For nuclei with $A>90$ statistical decay seems to be dominant, although a small contribution of semi-direct decay has been observed [1–4]. For lighter nuclei, the semi-direct decay mode becomes increasingly important. For ^{58}Ni a recent study claims a 40% non-statistical decay mode in the GR excitation energy region [5]. Also for nuclei with $A\leqslant 40$ appreciable non-statistical, semi-direct decay has been observed [6,7].

In addition to the well-known statistical and semi-direct decay modes there might well be other modes, e.g., pre-equilibrium modes resulting from the decay of a not-yet-fully equilibrated system. An example of such a mode is connected with the coupling of the giant resonances to low-lying vibrational or rotational modes. Decay via such a coupling has been predicted to be important for resonance decay in heavy nuclei [8].

In this paper we present data on the decay of the GMR and the underlying continuum in ^{124}Sn. The data show, for the first time, that the branching ratios of the various processes contributing to the decay of a giant resonance, in this case the GMR, depend on excitation energy. Furthermore, the data show evidence of pre-equilibrium decay, which can be attributed to the coupling of the GMR to low-lying 2^+ and 3^- states in ^{124}Sn. Finally, the decay of the continuum underlying the GMR was found to be different from that of the GMR.

The GMR in ^{124}Sn was excited by inelastic scattering at forward angles, including 0°, of 120 MeV α-particles obtained from the KVI cyclotron. Beam preparation and the setup has been described in ref. [2]. The width of the beam-pulse was around 1 ns and the overall time resolution 2 ns. The QMG/2 magnetic spectrograph was used to separate the inelastically scattered α-particles from the primary beam and to measure the momentum and angle of the scattered particles. Around the target, at a distance of 160 cm, 8 liquid scintillators were positioned at angles ranging from 45° to 165° to detect decay neutrons in coincidence with inelastically scattered α-particles. Pulse-shape discrimination was used to separate neutrons from γ-rays. The characteristic angular distribution of a $J^\pi=0^+$ excitation was used to determine the contribution of the GMR to the excitation spectrum, in singles as well as in coinci-

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dence with neutrons. It has a very pronounced maximum at 0°, whereas for this combination of beam energy and target it has a deep minimum about 3°. The angular distribution of higher multipolarities ($L \geqslant 2$) is almost flat in this region. By subtracting a spectrum, for α-scattering angles $1.5° \leqslant \theta_{\alpha'} \leqslant 3.0°$, from a spectrum for $\theta_{\alpha'} \leqslant 1.5°$, one obtains a spectrum that corresponds mainly to excitation of $L=0$ strength in the target nucleus, similar to fig. 6d of ref. [2]. The GMR bump for ^{124}Sn has a width of 3.4 MeV and is centeered around $E_x = 15.35$ MeV. The spctrum for $1.5° \leqslant \theta_{\alpha'} \leqslant 3.0°$ which is almost free of $L=0$ contributions [2] is defined as continuum as far as the region of the GMR is concerned. It may, however, contain contributions from higher multipolarities (see also figs. 6c and 15b of ref. [2]). For further details on the data analysis and definition of spectra see ref. [2].

By combining for each event the energy of the inelastically scattered α-particle with the energy of the emitted neutron, the final-state spectra of the residual nucleus ^{123}Sn were constructed. In figs. 1a–1c (the upper row), such spectra are shown for $-3° \leqslant \theta_{\alpha'} \leqslant 3°$, with the neutrons detected at 45°. In figs. 1g–1i (the lowest row), the corresponding spectra are shown for α-particles scattered from 1.5° to 3.0° and neurtons detected at angles $\leqslant 105°$. These spectra would then correspond to the decay of the continuum under the GMR (see for instance figs. 6c and 15b of ref. [2]). Finally, in figs. 1d–1f (the middle row), the final state spectra are shown for neutron angles $\geqslant 105°$, in which the spectra obtained for

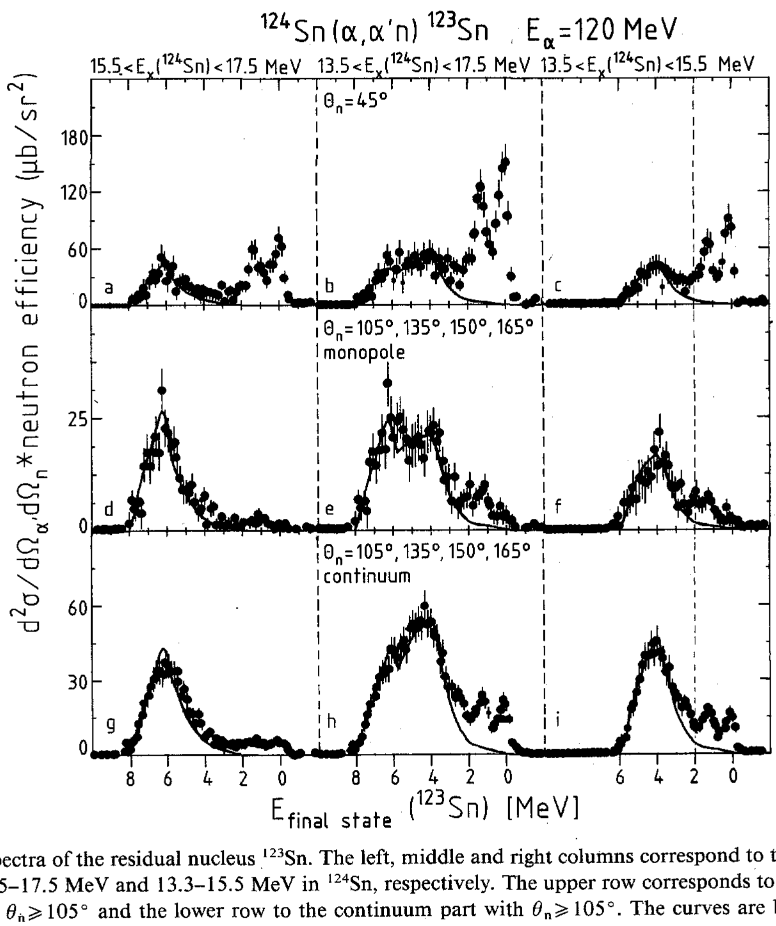


Fig. 1. Final-state spectra of the residual nucleus ^{123}Sn. The left, middle and right columns correspond to the excitation energy regions 15.5–17.5 MeV, 13.5–17.5 MeV and 13.3–15.5 MeV in ^{124}Sn, respectively. The upper row corresponds to $\theta_n = 45°$, the middle row to the GMR part with $\theta_n \geqslant 105°$ and the lower row to the continuum part with $\theta_n \geqslant 105°$. The curves are based on a statistical model calculation with the code CASCADE.

$1.5° \leqslant \theta_{\alpha'} \leqslant 3.0°$ have been subtracted from the spectra obtained for $\theta_{\alpha'} \leqslant 1.5°$: this final-state spectrum then corressponds to decay of the GMR proper [2]. The final-state spectra corresponding to the excitation energy regions 15.5–17.5 MeV, 13.5–15.5 MeV and 13.5–17.5 MeV in ^{124}Sn are shown in the left, right and middle column, respectively.

In figs. 1a–1c the contribution of the knock-out process can early be seen. This process gives forward-peaked neutron distributions in the recoil center of mass and populates the hole states in the residual nucleus. The angular correlation of neutrons leading to hole states in ^{124}Sn was found to be the same as obtained for ^{208}Pb in fig. 12 of ref. [2]. As shown in figs. 1g–1i, there is still an appreciable population of the hole states in the decay of the continuum below the GMR, although the contribution of knock-out for these large angles is expected [2] to be negligible.

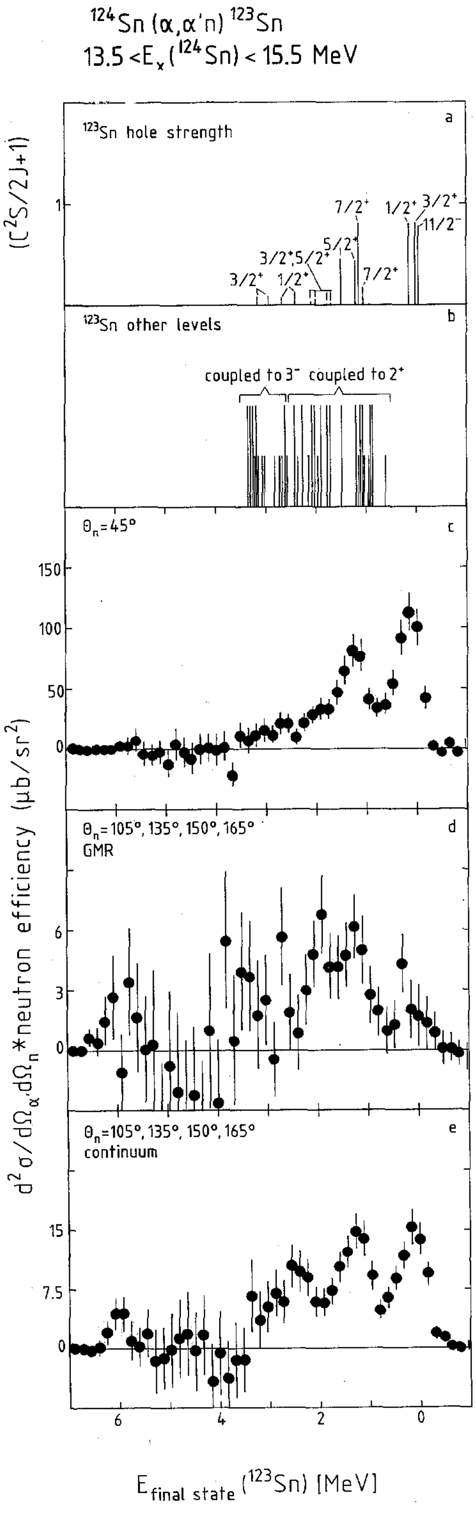
Statistical model calculations were performed with an extended version of the code CASCADE [9]. As level density input into this code individual levels in ^{123}Sn were used below 1.2 MeV [10], whereas above 1.2 MeV level density parameters were used which reproduce the cumulative number of levels up to 2.25 MeV and the number of s-wave resonances at the neutron binding energy (5.95 MeV) [11]. The curves in figs. 1a–1c and 1g–1i correspond to statistical model calculations of 2^+ strength having a strength distribution corresponding to the actual measured α'-spectrum between 1.5° and 3.0°. In these calculations, the efficiency and resolution of the neutron detectors as a function of neutron energy were folded in. The calculation was normalized to the total number of counts in the excitation energy intervals 3.0–6.0 MeV, 4.0–8.0 MeV and 5.0–8.0 MeV in ^{123}Sn for the low, total and high energy bins, respectively. For the continuum the intensity in the statistical part of the spectrum was found the same at forward and backward neutron angles.

As seen in figs. 1g–1i the calculations nicely reproduce the features of the spectra in the region from 3 to 8 MeV. The dip in the calculation just below 6 MeV originates from the opening of the 2n channel and is also seen in the data. The assumption of $J^\pi = 2^+$ for the continuum is not of crucial importance since for a calculation assuming $J^\pi = 3^-$ or $J^\pi = 4^+$ the fit is equally good. It is clear that the calculations by no means reproduce the decay strength to the low-lying hole states in ^{123}Sn. The non-statistical decay strength of the continuum is found to be approximately (15±5)%.

The same procedure was followed for the spectrum of figs. 1d–1f but here the actually measured 0^+ strength distribution was used. Figs. 1d–1f show also for the monopole a significant non-statistical decay, which is different from that of the continuum. A feature clearly illustrated by these data is that of the lower excitation energy part of the GMR (fig. 1f) is different from that of the upper part (fig. 1d). We find that the lower part has a non-statistical decay branch of 20%, whereas this is only 10% for the upper part. (These numbers have a systematic error of ±5%; relative errors are smaller than 2%.) Such an effect has not been reported before. It indicates that for the GMR the contribution of coupling to more complex states (spreading width) increases width excitation energy.

The features of the non-statistical part of the data are more clearly exposed in fig. 2 where the final state spectra for $13.5 \leqslant E_x \leqslant 15.5$ MeV are displayed after subtraction of the calculated contribution of the statistical decay. Also shown in fig. 2 is a summary of the level scheme of ^{123}Sn [10]. In fig. 2a the energy and spectroscopic strength of hole states in ^{123}Sn as observed in the ^{124}Sn(p, d) and ^{124}Sn(d, t) reactions [12] are given. In fig. 2b the other known levels in ^{123}Sn are summarized. The full size bars correspond for the GMR to decay with $l \leqslant 2$ and the half size bars to decay with $l \geqslant 3$ decay. Some of these levels between 1 and 2 MeV excitation energy are known phonon–hole coupled states with a neutron–hole coupled to 2^+ phonon [10]. States due to coupling of a hole to a 3^- phonon are expected between 2.6 and 4.0 MeV.

A comparison of the spectra reveals a qualitative similarity between those of figs. 2c and 2e, the main difference being that in the $\theta_n = 45°$ spectrum the hole states are relatively much more strongly populated than in the one for $\theta_n \geqslant 105°$, as expected when the knock-out process contributes. The GMR decay spectrum (fig. 2d) shows different features though. In this spectrum the group of states near the ground state is only weakly populated. This is presumably because of the weaker population of the $11/2^-$ ground state due to the smaller transmission coefficient. Sig-



◀ Fig. 2. (a) Spectroscopic strength and J^{π} values for hole states in ^{123}Sn. (b) Other levels in ^{123}Sn. Full size bars correspond for the GMR to decay with $l \leqslant 2$ decay, half size bars to decay with $l > 2$. (c)–(e) non-statistical part of the decay spectra corresponding to $13.5 < E_x(^{124}\mathrm{Sn}) < 15.5$ MeV for (c) $\theta_n = 45°$, (d) the GMR ($\theta_n \geqslant 105°$) and (e) the continuum under the GMR ($\theta_n \geqslant 105°$).

nificant differences also occur in the excitation energy range from 1.5 to 3 MeV. The GMR decay in fig. 2d has a maximum at 2.0 MeV followed by a dip at 2.5 MeV whereas in the decay spectrum of the continuum of fig. 2e is a dip at 2.0 MeV and a relative maximum at 2.5 MeV. Since for $E_x > 1.5$ MeV there is no appreciable hole strength present, this already indicates that for decay to states between 1.5 and 3 MeV preequilibrium decay could play an important role. Considering that in the energy region around 2 MeV many hole–2^+ photon-coupling states are expected (fig. 2b) this intensity could be interpreted to be due to GMR–phonon coupling. Also part of the intensity around 1 MeV could be due to decay to hole–phonon coupled states. Coupling of the GMR to the 3^- phonon would give decay to phonon–hole coupled states between 2.6 and 4.0 MeV. Some excess intensity is observed in the final- state spectra of both the GMR and the continuum in this region. Thus part of the non-statistical fraction of the decay of the GMR in the energy bin $13.5 \leqslant E_{\alpha'} < 15.5$ MeV might well be due to coupling to low-lying surface vibrations.

Some indications of the phenomena described above have been observed in previous experiments. In an experiment on the decay of the GMR in ^{208}Pb [2] the data were found to be consistent with 100% statistical decay. An alternative analysis of the data, however, indicated that at maximum 30% of the decay could be attributed to pre-equilibrium decay to hole–phonon coupled states and 10% to semi-direct decay to hole states. The Erlangen group found a non-statistical decay branch of 15% for the GMR in ^{208}Pb and ^{90}Zr, of which they could ascribe ~5% to pre-equilibrium decay [3]. However, as shown in ref. [13] the Erlangen data on ^{208}Pb are also consistent with a completely statistical decay. The Osaka group [4] has reported a 20% non-statistical decay branch for the GQR in ^{119}SN and ^{92}Zr, but this was entirely due to semi-direct decay to hole states. The present data on the decay of the GMR in ^{124}Sn present the first clear evidence in particle decay work for a non-statistical and non-semi-direct decay component which is consistent with one expects from a pre-equilibrium decay if GMR–phonon coupling contributes to the damping process.

The authors would like to thank Dr. P. Decowski for his help in the startup of this experiment and Dr. R.F. Carlton and Dr. J.A. Harvey who communicated their data on s-wave resonances in $^{122}Sn+n$. The financial support from the Swedish Science research council (N.F.R.) is gratefully acknowledged. This work was performed as part of the research program of the Stichting voor Fundamenteel Onderzoek de Materie (FOM) with financial support from the Nederlandse Organisatie voor Zuiver Wetenschappelijk Onderzoek (ZWO).

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